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A Critique of Wolak's Evaluation of the NZ Electricity Market:

The Incentive to Exercise Market Power with Elastic Demand and Transmission Loss

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Abstract:

This paper is the second in a symposium of papers that examine the 2009 report by Frank Wolak into the New Zealand electricity market. In this paper, we discuss the Report's measures of the ability and incentives of generators to exercise unilateral market power. We show that the construction and interpretation of these measures are highly sensitive to some key assumptions, particularly those concerning the elasticity of demand for electricity in the wholesale market and the amount of transmission loss on the national grid.

Key Words: Wolak Report; electricity markets; market power.

JEL Codes: L41, L13

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1. Introduction.

As mentioned in the first of the papers in this symposium[1], the Wolak report (Wolak, 2009) contained three broad strands of empirical evidence that generators have exercised substantial market power to generate wholesale prices in excess of marginal cost. The earlier paper discussed the third of these approaches, used to construct the headline figure of $4.3b of overcharging, which required a direct estimate of generators' marginal costs.

In this paper, we consider the first strand of evidence of putative overcharging in the Wolak report. This approach used the information contained in the historical supply offers made by generators to calculate the ability and incentive of firms to force the wholesale market price above marginal cost by withholding supply from the market. Under the maintained assumption that generators choose to exercise all available market power to maximise profit, measures of the incentive to exercise market power can be used to infer indirectly the extent to which prices have been elevated above marginal cost and thus bypass the need to estimate marginal cost directly.

It is important to note that it is not obvious that firms would choose to exercise all available market power. First, three of the four large generators are state-owned-enterprises, and although their primary objective under the State-Owned Enterprises Act is "to be as profitable and efficient as comparable businesses that are not owned by the crown", the act also specifies that they should be "an organisation that exhibits a sense of social responsibility by having regard to the interests of the community in which it operates and by endeavouring to accommodate or encourage these when able to do so".[2] Second, and more important, the threat of entry, government regulatory intervention, or long-term consumer substitution away from electricity use can provide a long-term profit-maximising rationale for not fully exploiting market power in the short-run.

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[1] Evans, Hogan and Jackson (2011).

[2] State-Owned Enterprises Act (1986).

Our focus in this paper, however, is not with this broader question of whether one can infer excess price from measures of the incentive to exercise market power, but with whether the approach used in the Wolak report to calculate the incentive measures is correct. In particular, the report's approach assumes zero elasticity of demand and zero transmission loss between the points at which electricity is injected into the national grid and the points at which it is extracted. While reasonable simplifying assumptions in many contexts, we show in this paper that they have the effect of biasing up the estimates of incentive to exercise market power.

In the following section, we describe the process by which wholesale market prices are determined in New Zealand and hence how an individual firm can, in principle, use its market power to influence those prices. In Section 3, we briefly summarise the theory underlying the construction in the Wolak report of measures of the ability and incentive to exercise market power. In Section 4, we show how these measures need to be adjusted to take into account demand elasticity and transmission loss. Section 5 then discusses how substantial these adjustments might be empirically. Section 6 briefly concludes.

2. Wholesale Price Determination.

The backbone of the wholesale electricity market in New Zealand is the national grid of high-voltage transmission, which contains a number of "injection points", where generators sell into the grid, and "exit points", where buyers purchase. The market consists of a set of prices at each injection and exit point every half hour, with the prices set to equate supply and demand taking into account transmission losses along the grid.

Suppliers submit offers every half hour. These offers take the form of a 5-step, piece-wise linear supply curve. Price determination is then based on a uniform-price auction in which each supplier receives for all units sold the price required to induce the marginal unit supplied at a particular injection point.

Buyers do not submit demand curve bids in an analogous form to supply; rather they just draw whatever quantity is desired. Further, because power is consumed instantaneously, prices cannot be communicated to buyers in advance of purchase and so must be determined ex-post. This implies a zero elasticity of demand in the extreme (30 minute) short run.

Although suppliers' offers consist of quantity-price pairs to create a supply schedule, and not just a fixed quantity, this form of uniform-price auction closely resembles a Cournot quantity-setting market. By submitting an inflated supply curve (i.e. specifying a price greater than marginal cost as being the minimum needed to induce supply of that marginal quantity), a generator can cause the market-clearing price to be higher, at the cost of seeing a reduced quantity sold. The ability of any firm to exercise this market power obviously depends on the elasticity of demand and the elasticity of supply of the other firms in the market. As in any Cournot market, the greater is the market share of a firm, the greater is this effective market power.

As is typical with electricity markets, generation in New Zealand is dominated by a small number of firms. (In 2003, the four largest generators in New Zealand were responsible for 86% of total generation, and the five largest for 91%.[3]) Furthermore, because the market is simultaneously cleared at many nodes and there are often limited generation options in the short term in a particular location, the cost of supplying power to a particular exit node can increase significantly. In times of system stress when other generation options are at full capacity and/or transmission lines are constrained, this effect is exacerbated. As a result, although there are five large companies and many smaller fringe generators operating in the NZEM, the ability of other generators to respond in a competitive fashion to a withdrawal of supply in a particular region is limited. In such cases, the restraint on the ability of firms to exercise market power must come from the elasticity of demand.

3. Measures of the Ability and Incentive to Exercise Unilateral Market Power.

In this section, we present the theory for how one can begin to infer from market data on firms' offer curves, each firm's ability and incentive to inflate wholesale prices by overstating the prices at which they would be willing to supply given quantities.

Consider, first, a simple Cournot model with no transmission loss and no vertical integration. Let $S_j(p)$ be the offer curve (supply) submitted by generator *j*, and let the demand curve be $D(p)$. The residual demand curve, $R_i(p)$, facing firm *i* gives the quantity that firm *i* would need to supply into the market to produce a market price of *p*, taking the demand curve and the offer curves of the remaining generators as given. That is

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[3] See Evans and Meade (2005, Table 3.5).

$$R_i(p) = D(p) - \sum_{j \neq i} S_j(p).$$

Let $c_i(q_i)$ be firm *i*'s cost of supplying q_i units of output. Firm *i*'s profit maximisation problem then is

$$\underset{p}{Max} \quad pR_i(p) - c_i(R_i(p)),$$

for which the first-order condition is

$$(p - c_i')R_i'(p) + R_i(p) = 0.$$

This equation can be re-written as

$$p = c_i' + 100\eta_i, \tag{1}$$

where

$$\eta_i = -\frac{R_i(p)}{100R_i'(p)}. \tag{2}$$

The term, η_i, is what the Wolak report terms an "inverse semi-elasticity". It measures the amount by which a generator could increase price by withholding 1% of its supply from the market and so is a measure of the market-power of a single firm. In the case where firms have no fixed-price forward contracts and no other limiting factor restraining their tendency to exercise market power, as shown by Equation (1), it is also a measure of the incentive of a firm to withhold supply in order to push price higher than marginal cost.

If firms do have a commitment to sell a certain amount of power at a fixed price determined prior to submitting supply offers into the market, then, while η_i still reflects a firm's *ability* to exercise market power, the incentive to do so is mitigated by the extent to which it needs to be a buyer in the wholesale market in order to meet its fixed-price obligations. To show this, let generator *i*, have fixed-price forward contracts to sell a quantity, Q_i, of power at an average price of $\overline{p}$.[4] In this case, the firm's optimisation problem becomes

$$\underset{p}{Max} \quad pR_i(p) - c_i(R_i(p)) + (\overline{p} - p)Q_i, \tag{3}$$

and the associated first-order conditions and semi-elasticity mark-up rule become

$$(p - c_i')R_i'(p) + (R_i(p) - Q_i) = 0, \text{ and}$$

[4] Since $\overline{p}$ has no effect on the firm's offer strategy, it doesn't matter for the theory whether all its fixed-price obligations are at the same price or contract-specific prices.

$$p = c_i' + 100\eta_i \cdot \delta_i, \tag{4}$$

where

$$\delta_i = \frac{R_i(p) - Q_i}{R_i(p)}. \tag{5}$$

The mitigation term, δ_i, gives the extent to which fixed-price forward obligations reduce the incentive to exercise market power. In the special case where the generator will supply exactly the same quantity of power as its forward obligation, the mitigation is 100% and the optimal quantity will be such that price equals marginal cost. If its forward obligations are greater than its quantity supplied, the incentive is to expand output to force prices lower.

4. Potential Modifications to the Measures.

The theory laid out in the previous section replicates, with slight notation changes, that presented in the Wolak report. Of course, the theory describes the incentives facing firms in a very simple model that abstracts away from many features of the actual New Zealand electricity market. Given the complicated nature of that market, some degree of simplification is necessary to get a tractable model, but considerable caution is then needed before interpreting measures based on the simplified model. There are two aspects of reality in particular that, if not considered, will lead to a biasing up of the estimates of η_i and δ_i and consequently of the estimates of the incentive to exercise market power. The first concerns the impact of the elasticity of demand for wholesale-market electricity on the calculation of η_i, and the second concerns the impact of transmission loss on the formula δ_i.

4.1 The impact of demand elasticity on market power.

As noted in the previous paper in this symposium, the Wolak report assumes that demand is perfectly inelastic. This is a perfectly sensible assumption for the short-run elasticity, and so might accurately represent the fleeting market power that could result from, say, a temporary failure in the transmission network. However, the seasonal nature of power crises in New Zealand results in prices being consistently high over a period of weeks or months, and as described in the earlier paper, the market contains mechanisms by which load can and does respond to price incentives.

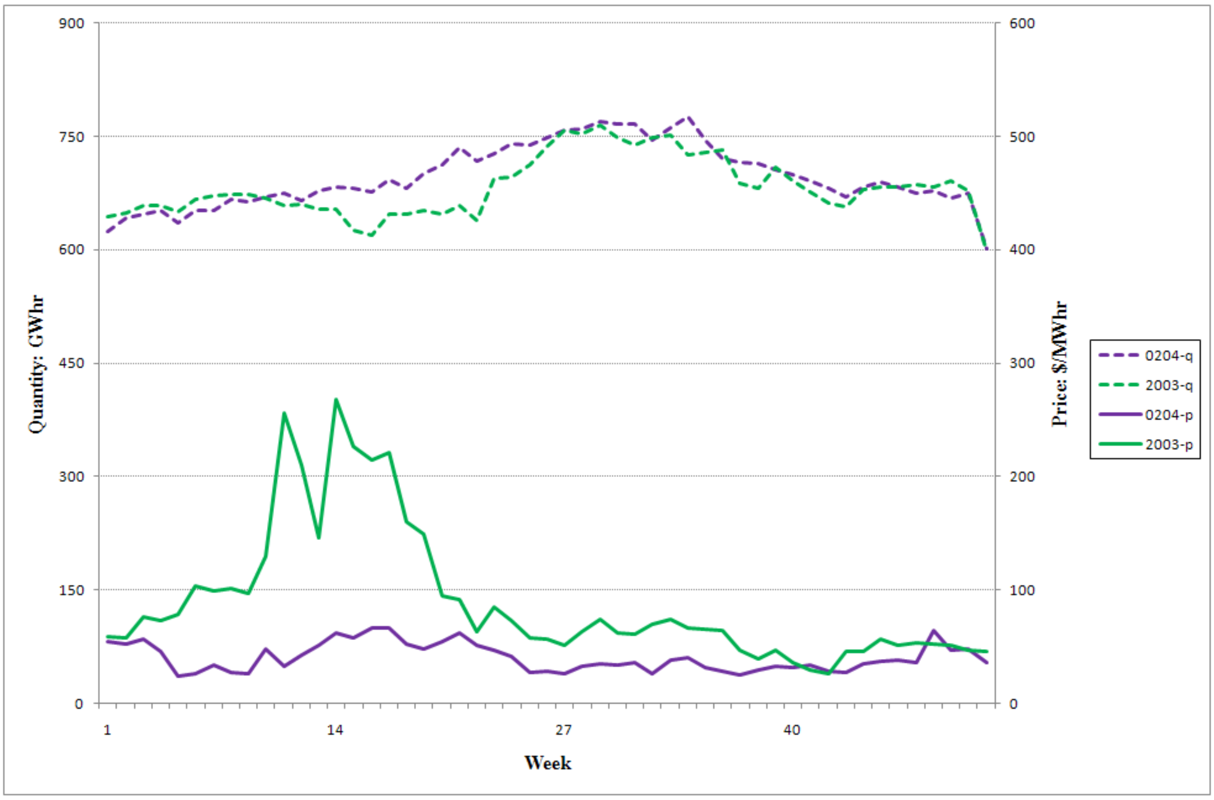
To illustrate this, consider Figure 1 below, which shows total weekly offtake from the grid and a weighted average of price by week for the three years from 2002 to 2004. 2003 was a dry year in which hydro storage got as low as 55% of normal, seasonally adjusted, levels by April before recovering to normal levels by July; in 2002 and 2004 hydro storage was at or above their historical levels. This is reflected in price, which was remarkably consistent over time over the three years, except for the low-storage period in 2003. Figure 1 shows a general trending up of quantity over time, but with a relative fall in quantity for a period following the price spike in 2003.

Figure 1: Wholesale Quantity and Price—2002-2004.

The unusual pattern in 2003 is more clearly shown in Figure 2, which compares quantity and price in 2003 to an average of 2002 and 2004. The unseasonable price spike started around week 11 before returning close to normal levels around week 22, quantity followed a similar inverse pattern, but with an approximate 5 week lag, being at its lowest level relative to the 2002-04 norms in week 16 and returning to normal levels in week 27.

The point here is that generators looking to exploit market power over longer periods, may well face perfectly inelastic demand curves in the very short-run of a single 30-minute pricing period, but they must also take into account the impact that persistent high prices will have on that inelastic short-run demand curve over time.

Figure 2: Wholesale Quantity and Price—2003 versus 02-04 average.



This is particularly pertinent in assessing measures of market power. Although a small amount of demand elasticity will not have much impact on the semi-elasticity most of the time, it can have a very large impact when the semi-elasticity is very high. To see this, imagine that we have an estimate of the market-power elasticity, $\hat{\eta}_i$, made under the assumption that demand elasticity is zero when the absolute elasticity is in fact positive. Note that

$$-R_i'(p) = \sum_{j \neq i} S_j'(p) - D'(p).$$

We therefore have

$$\eta_i = \frac{R_i(p)}{100(\sum_{j \neq i} S_j'(p) - D'(p))} \tag{6}$$

while

$$\hat{\eta}_i = \frac{R_i(p)}{100 \sum_{j \neq i} S_j'(p)}. \tag{7}$$

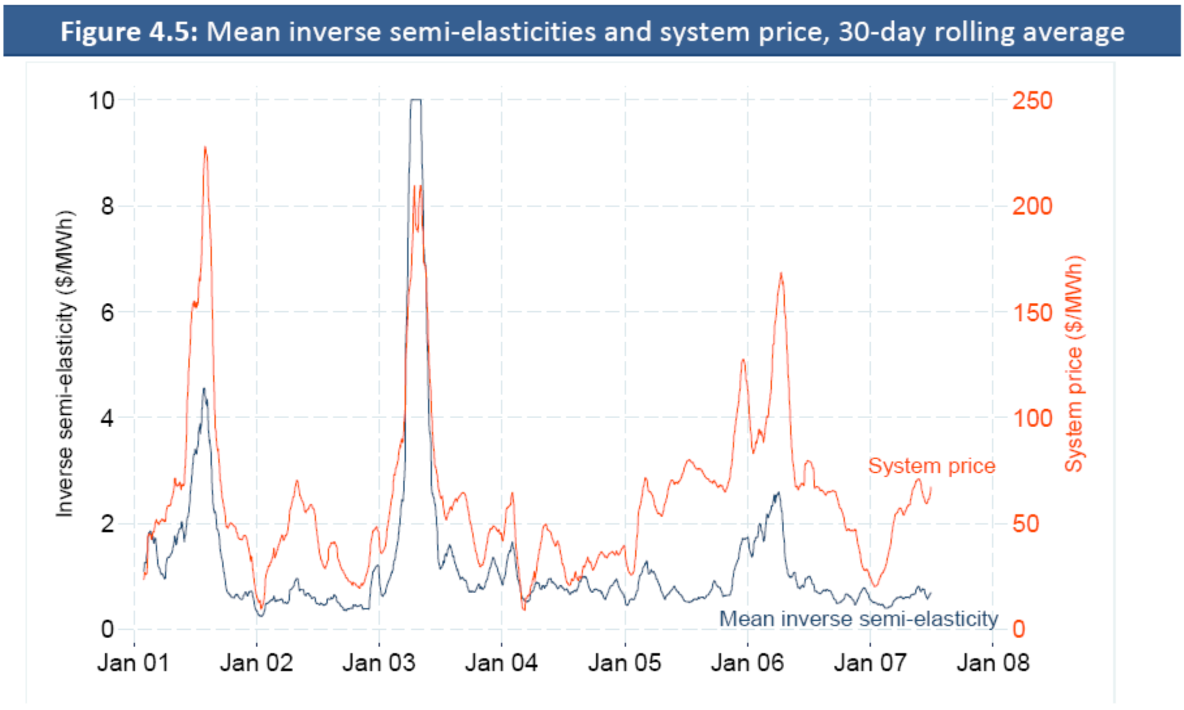
Putting Equation (7) into (6) gives

$$\eta_i = \frac{1}{\frac{1}{\hat{\eta}_i} + \frac{\varepsilon 100 \theta_i}{p}}, \tag{8}$$

where $\varepsilon = -pD'(p)/D(p)$ is the absolute elasticity of demand and $\theta_i = D(p)/R_i(p)$ is the inverse of firm *i*'s market share.

Now consider Figure 3 below, which reproduces Figure 4.5 from the Wolak report. The highest average (across all generators) value for the estimated inverse semi-elasticity, $\hat{\eta}_i$, is 10, which occurred at the peak of the dry-year price-spike of 2003. That corresponded to a market wholesale price of 200. If we generously assume an inverse market share of $\theta_i = 4$, then a demand elasticity as low as $\varepsilon = 0.05$ would be enough to lower the true inverse semi-elasticity from 10 to 5, thereby halving the estimated incentive to exercise market power.

Figure 3: Wolak Report Estimates of Market Power



4.2. The Impact of Transmission Loss on the Incentive to Inflate.

The model presented in Section 2 describes a network with no transmission loss. In reality, firms supply power to "injection points" on the national grid, and demanders in the wholesale market purchase power from "exit points". The offers of generators are offers to supply a quantity of electricity at the injection point at the specified prices, whereas the prices paid by buyers refer to the quantity taken at the exit points. With transmission loss along the grid, the total quantity supplied at injection points must exceed that demanded at exit points, with a corresponding differential in the prices.

To see how this can affect the empirical estimates of the incentive to inflate, consider a slight modification to the model of Section 2, by considering a two-node system in which all generators supply at one node, and demanders purchase at the other. Further, assume that an expected fraction, λ, of the energy supplied is lost in transmission.

Let $\hat{\delta}$ be the mitigation measure derived assuming no transmission loss, according to Equation (5), and let δ be the true level of mitigation taking transmission loss into account.

Let $S(p^s)$ be the total energy supplied at the injection node as a function of the price received by sellers, and let $D(p^d)$ be the total energy demanded at the exit node, as a function of the price paid by buyers. Equilibrium in this market requires that the energy supplied is enough to meet demand taking into account the transmission loss,

$$D(p^d) = (1-\lambda)S(p^s)\,, \tag{9}$$

and that the prices are such that total payments equal total receipts,

$$p^d D(p^d) = p^s S(p^s). \tag{10}$$

Equation (9) into (10)gives

$$p^d = \frac{p^s}{1-\lambda},$$

and the modification to Equation (3) to account for transmission loss is

$$\underset{p^s}{Max} \quad p^s R_i(p^s) - c_i(R_i(p^s)) + (\overline{p} - p^s/(1-\lambda))Q_i,$$

for which the first-order condition is

$$\begin{aligned} p &= c_i' + \frac{R_i(p)}{R_i'(p)} \cdot \frac{R_i(p) - Q_i/(1-\lambda)}{R_i(p)} \\ &= c_i' + 100\eta_i \cdot \frac{\hat{\delta}_i - \lambda}{(1-\lambda)}. \end{aligned} \tag{11}$$

That is, we have

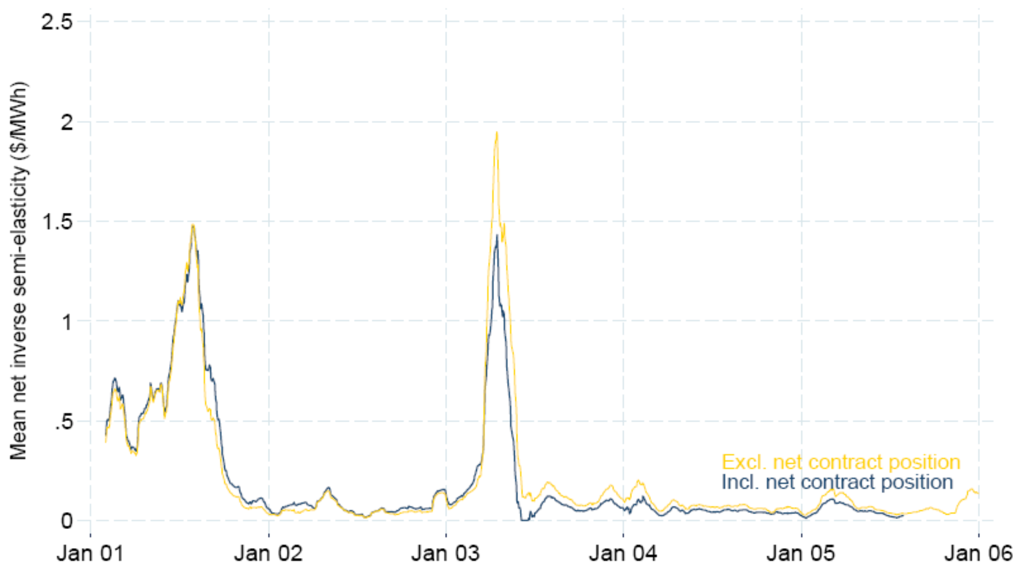
$$\delta_i = \frac{\hat{\delta}_i - \lambda}{(1-\lambda)}. \tag{12}$$

To get a sense of how important transmission loss might be, consider Figure 4 below, which reproduces Figure 4.8 from the Wolak report. Again, we focus on the dry-year price spike in 2003. The mean net inverse semi-elasticity at the peak, taking into account both vertical integration and generators' fixed-price forward contracts, is approximately 1.5. Recall from the previous graph that the mean inverse semi-elasticity was 10. That is, we have mean values of $\overline{\eta} = 10$ and $\overline{\eta\delta} = 1.5$, and so can infer a mean value of δ_i of approximately 0.15.[5] Accordingly, even quite small amounts of transmission loss could have a large effect on the estimate of the incentive to exercise market power in 2003.

In the following section, we provide some suggestive estimates of how consideration of both demand elasticity and transmission loss can strikingly change this estimated incentive.

Figure 4: Wolak Report Estimates of Market-Power Incentive:

Figure 4.8: Mean net inverse semi-elasticities with and without forward contracts



Source: Calculations based on offer and generation data from Centralised Data Set and EMS, firm-level settlement data from EMS, dispatch data from M-Co, and contract data from individual firms.

[5] These figures are very approximate as, in general, the mean of the product of two numbers is not the product of the means—that is, $\overline{\eta\delta} \neq \overline{\eta}\overline{\delta}$. Without firm-level data, however, this is the best approximation available.

5. Implications for Estimates of Overcharging.

The Wolak report's direct estimate of $4.3b of market rents earned from the exercise of unilateral market power came mostly from the three high-price periods, in 2001, 2003, and 2006, respectively. The estimation method assumed that true marginal cost was not significantly higher in those periods, and so all of the price increases could be attributable to market power.

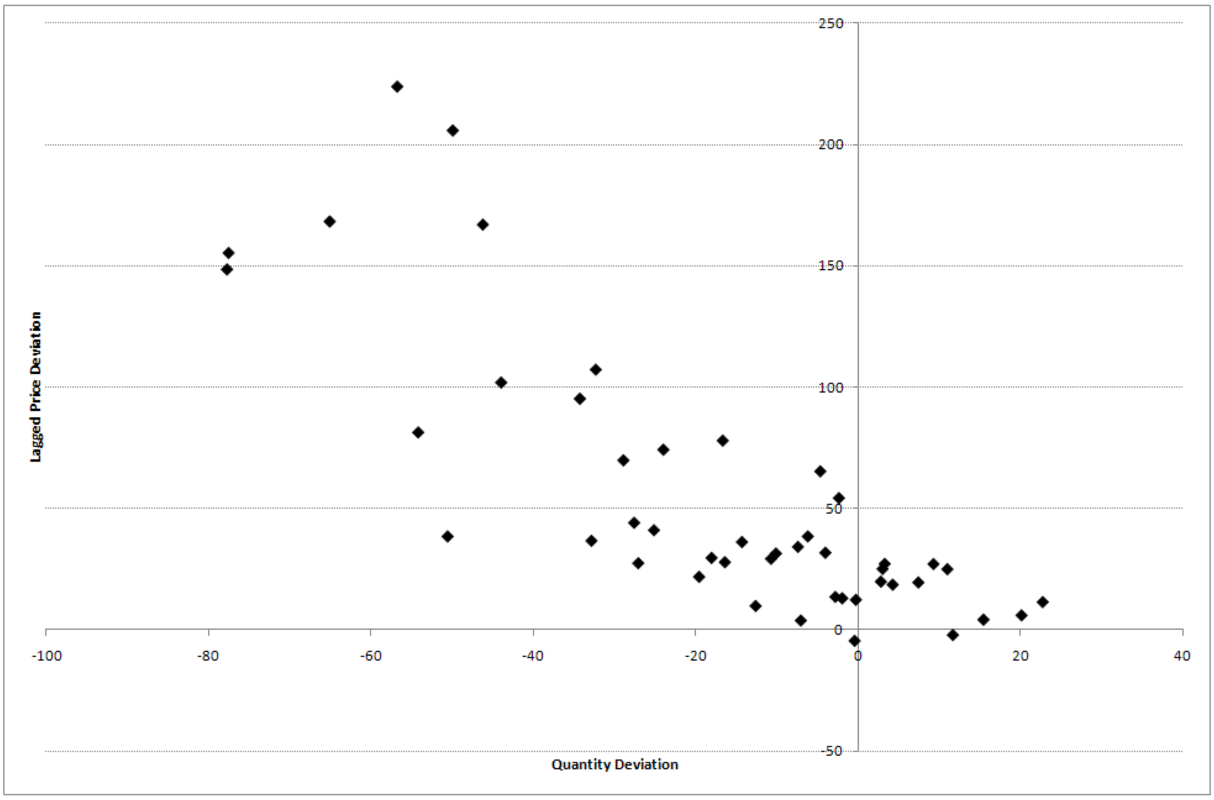
This is consistent with the estimates of the market-power incentive shown in the Report's Figure 4.8 (Figure 4 in this paper). For instance, in both the 2001 and 2003 price spikes, the calculated net inverse semi-elasticity was 1.5 implies that generators would have been setting prices approximately $150/MWh above marginal cost, if they were choosing to maximise short-run profit. As can be seen in the Report's Figure 4.7 (Figure 3 in this paper), this is roughly the same amount that prices at the peak were above their normal levels.

Even assuming the maintained assumption of short-run profit maximisation is valid, the adjustments suggested in this paper could imply a very different interpretation of the high prices. It is beyond the scope of this paper to undertake a complete recalculation of the measures of the incentive to inflate, partly as that would require access to confidential data regarding generators' historical net contracting positions. We can, however, provide some indicative calculations of how sensitive the measures are to our suggested adjustments.

Consider first the elasticity of demand. We are interested in the effect that very high wholesale-market prices, such as those experienced in 2001 and 2003, have on wholesale-market demand, since those are the periods where the estimated incentive-to-inflate measures are high. We consider, then, the data shown in Figures 1 and 2 above.[6] There is a clear seasonal effect to quantity and, to a lesser extent, price, with a clear deviation from that seasonal norm for each series in the second quarter of 2003. As we noted earlier, there also appears to be an approximate 5-week lag between the price deviation from norm, and the quantity deviation. Figure 5 illustrates this pattern, graphing the deviation of 2003 price from its 2002/2004 average for the same week of the year versus the 5-week lag of the deviation of quantity from its 2002/2004 average.

6 We focus on the 2003 dry year, as this is the one where, as we shall show, the measure of the incentive to exercise market power is most sensitive to the assumption of zero elasticity of demand.

Figure 5: Quantity Shock versus Lagged Price Shock—2003.



To provide a tentative estimate of this apparent relationship between lagged price and quantity, we regress the quantity deviation on the contemporaneous price deviation and five lags of the price deviation. The sum of the coefficients on price deviation and its lags is -0.33, which would correspond to an absolute demand elasticity at the price peak of 2003 of $\varepsilon = 0.13.$ We stress here that this simple regression does not constitute a serious econometric estimate of the wholesale market demand curve. Rather, we treat the regression coefficients as a descriptive statistic of the relative magnitudes of the shocks to price and quantity that occurred in 2003 in order to create a reasonable point-estimate guess of elasticity that can be used to illustrate the sensitivity of results to a zero-elasticity assumption. In the appendix, we provide more details of the estimated equation.

We now consider transmission loss. Accurate data for transmission loss between injection and exit points on the grid is difficult to obtain. ETAG (2009) reported that total transmission loss in 2008 was 7.5%, of which 3.8 percentage points was loss on the national grid. In contrast, direct calculations made from the generation and load data in the Centralised Data Set put out by the former Electricity Commission, imply values in the range of 5.0%-

6.0%.[7] Given that transmission loss is greatest at times when load is high, particularly when the flow on the HVDC is high, and this is typically the times when demand puts the most pressure on price, a value of 5% seems a reasonable, conservative estimate for the transmission loss at times of price peaks.

Now consider Table 1, which presents the Wolak Report's estimates of the ability and incentive to exercise market power in the three peaks of 2001, 2003, and the mini peak at the end of 2005. Note that Figure 3 shows a further peak early in 2006, but this is beyond the period for which data is provided in Figure 4. The values for the reported ability to exercise market power, $\hat{\eta}$, and the incentive to exercise market power, $\hat{\eta}\hat{\delta}$, are approximate values read off the graphs presented in Figures 3 and 4 above. The values for the reported mitigation factor, $\hat{\delta}$, are inferred from these other two values.

Table 1: Wolak Report Measures of Ability and Incentive to Inflate for Three Peaks.

Year	$\hat{\eta}$	**Implied** $\hat{\delta}$	$\hat{\eta}\hat{\delta}$	**Excess Price**
2001	4.5	0.33	1.5	150
2003	10.0	0.15	1.5	150
2005	2.0	0.10	0.2	20

The comparison between 2001 and 2003 is particularly interesting here. The unadjusted data suggest the same incentive to exercise market power in 2001 and 2003, but that this arises from a much higher ability to exercise market power in 2003, coupled with that power also being mitigated by fixed price contracts to a much larger extent.

Now let's modify these measures using Equations (8) and (12) above. These results are shown in Table 2. In Equation (8) we again assume an average market share of 0.25, and hence set $\theta = 4$, and then set $D'(p)$ equal to the value of -0.33 taken from the linear demand curve estimated earlier in this section. This results in a substantial reduction in the implied ability to exercise market power in the 2003 peak, when $\hat{\eta}$ was very high, compared to the

7 We are grateful to Neil Walbran of *Neil Walbran Consulting* for providing us with this data. The data and calculations are available from the authors on request.

other two peaks. We then assume transmission loss of 5% $(\lambda = 0.05)$ to construct the revised measure of the mitigation effect, δ. This has a much larger proportionate effect in the peaks when the estimated mitigation effect without transmission loss was low. Again, this implies a much larger adjustment for the 2003 peak than for 2001.

Table 2: Adjusted Measures of Ability and Incentive to Inflate for Three Peaks.

Year	η	δ	$\eta\delta$	**Excess Price**
2001	2.49	0.30	0.74	74
2003	3.36	0.11	0.35	35
2005	1.43	0.05	0.08	8

The combined effects of these adjustments can be seen by comparing the assumed excess price for the three peaks in the two tables. Without the adjustments, the assumed excess price is about the same as the deviation of price form normal levels, as shown in Figure 3. With these adjustments the potential gains from the use of market power, is about half for the 2001 peak, and much lower for the 2003 and 2005 peaks.

The difference in the level of mitigation between 2001 and 2003 can be attributed mostly to the fact that in 2001, a substantial share of the retail market was held by *Natural Gas Corporation* (NGC), rather than a major generator, implying that the five major generators overall had a substantial net positive supply position in the wholesale market. Furthermore, in 2001 NGC had not purchased fixed-price forward cover to hedge against its own its fixed-price obligations to his retail customers. NGC sold its retail base to two of the major generators later in 2001, with the result that since then, generation and retail market shares have been closer to being balanced. Indeed, in January 2003, none of the five major generators had a net position greater than 2% in the wholesale market, and the two largest generators (Meridian and Contact) had negative net positions.[8] These data suggest that even the revised estimates of the mitigation factor, δ, given in Table 2 may be too high.

8 See Evans and Meade (2005, Table 3.5).

6. Concluding Remarks.

In this paper, we have sought to illustrate the sensitivity of the estimates of the ability and incentive to exercise market power contained in the Wolak Report to two key assumptions. With some relatively conservative assumptions about the elasticity of wholesale market demand, firms' market shares, and the extent of transmission loss, the estimated potential of market power is substantially lower for the 2003 and 2005 price spikes than was suggested by the Wolak Report. These reduced numbers are consistent with the fact that, through vertical integration, the major generators have largely balanced supply and demand positions in the wholesale market.

Our revised estimates are still consistent with the conclusion that market power was responsible for about half of the increase in prices in the 2001 dry year, which in turn is consistent with the lower level of vertical integration that existed at that time.

Our calculations here are intended to be suggestive of the sensitivity of market-power measures to assumptions about demand elasticity and transmission loss, rather than hard empirical estimates. We do believe, however, that they indicate that extreme caution is needed before concluding that the exercise of market power has played a major role in wholesale-market price fluctuations, at least since late 2001.

Finally, we again stress that firms would not necessarily want to exercise all available short-term market power, so even the revised estimates of market-power incentives that fully take into account demand elasticity and transmission loss can still be overestimates of the extent to which price has been inflated by market power. Indeed, as shown by Evans and Guthrie (2011) in the third paper in this symposium, such overestimates will be exacerbated by the fact that non-exercise of market power will typically lead to an upward bias in the measure of that power.

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Appendix: Estimate of Demand Elasticity

We postulate a linear demand for wholesale power of the form

$$q_t^y = \alpha + \sum_{\tau=0}^{T} \beta_\tau p_{t-\tau}^y + \gamma_y DY_y + \delta_t DW_t, \tag{A1}$$

where q_t^y and p_t^y are respectively the quantity demanded and price in week *t* of year *y*, DY_y is a set of year dummies to capture general increase in demand over time, and DW_t is a set of week dummies to capture seasonal shifts in demand throughout the year. We define week *t* in a particular year as being the 7 days starting from the *t*th Monday in that year.

We are interested in quantifying the demand reaction to the price spike in 2003. Accordingly, define

$$\hat{q}_t = q_t^{2003} - \frac{1}{2}\left(q_t^{2002} + q_t^{2004}\right), \text{ and}$$

$$\hat{p}_t = p_t^{2003} - \frac{1}{2}\left(p_t^{2002} + p_t^{2004}\right).$$

Equation (A1) can then be re-written

$$\hat{q}_t = \hat{\alpha} + \sum_{\tau=0}^{T} \beta_\tau \hat{p}_{t-\tau}, \tag{A2}$$

where the constant term is

$$\hat{\alpha} = \frac{1}{2}\left((\gamma_{2003} - \gamma_{2002}) - (\gamma_{2004} - \gamma_{2003})\right),$$

which is zero if there is a constant trend rate of growth in demand over the three years.

Estimating Equation (A2) with *T*=5, gives the following results:

Variable	Constant	p_t	p_{t-1}	p_{t-2}	p_{t-3}	p_{t-4}	p_{t-5}
Coefficient	0.5577	0.1079	0.0023	0.0665	-0.1046	-0.0670	-0.3317
p-value	.86	.15	.97	.44	.23	.45	.00

In regressions with five or fewer lags on *p*, the last lag is always highly economically and statistically significant; this is not the case with regressions with more than five lags. Also, there is a high degree of positive autocorrelation in the specifications with fewer than 5 lags. There is some evidence for autocorrelation with 5 lags, with a Durbin-Watson statistic of

1.50, with an associated p-value of 0.037, but adjusting for it has little affect on the estimated coefficients. Finally, an alternative specification assuming a log-linear (constant elasticity) demand function fits the data less well for a given number of lags than the equivalent linear specification.